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Soil-Structure Interaction Effect on the Optimal Design of Low-, Mid- and High-Rise Reinforced Concrete Frames

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ABSTRACT: In procedure for analysis, design and optimization of reinforced concrete buildings, for most or maybe all regular buildings, different parts of the procedure for different parts of the building, including main structure and its foundation, are usually carried out independently. This means that these structures are mainly analyzed and designed by supposing a fixed-base, and then, forces at the foot of columns are obtained and used to analyze and design the foundation. Thereby, no attention is paid to the effects of foundation settlements on the distribution of forces in structural elements. Interaction between the structure, the foundation and its subsoil (flexible-base), changes the actual behavior of the structure compared to the method in which the structure is investigated alone (fixed-base). In this paper, various RC buildings, including low-, mid- and high-rise types, with foundations and soil under their foundations in three different layers, with a depth of each layer equal to ten meters, are modeled using SAP2000. Also, all the frames are optimized using Artificial-Bee-Colony algorithm in MATLAB, subject to stress and drift constraints. The results show that, since in a structure with optimal design the values of stress in elements and drift of stories are usually very close to the maximum allowable limits, hence, a slight increase in structural response, induced by soil-structure interaction effects, may lead to the violation of optimal design constraints. Therefore, taking not into account such effects in design optimization of structure, may lead to not only a non-optimal but also an infeasible design.

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1- Introduction

In order to design a reinforced concrete moment frame, the current approaches model the structure as fixed-base; whereas, the flexibility of the base may have considerable contributions to the structural response. Hence, the Soil-Structure-Interaction (SSI) effects must be accounted for in the design of such buildings, especially when the optimal structural design is pursued.

Nowadays, the ever-increasing rate of construction and material costs urges designers to optimize the design of the structures. It is well-known that in most cases, in an optimal structural design, the values of the structural responses are very close to the allowable limits (design optimization constraints); hence, the response of the structure must accurately be evaluated. Therefore, SSI effects may substantially alter the optimization results. Although numerous literature studies are focusing on design optimization of structures (e.g. [1-2]), but in very rare cases the SSI effects are accounted for [3-4].

The review of the literature shows that the previous studies are limited to bridges, steel frames, and simple design optimization with no SSI accounted for. In the present study, RC frames are optimized with the SSI effects accounted for. For this aim, three examples of low-, mid-, and high-rise buildings are studied and the optimal structural designs obtained in fixed-base and flexible-base cases are compared and discussed.

2- Methodology

Generally, to investigate the flexible base, the soil can be modeled using one rotational (k_{yy}) and two translational (k_x , k_z) springs as shown in Figure 1. This approach can also be

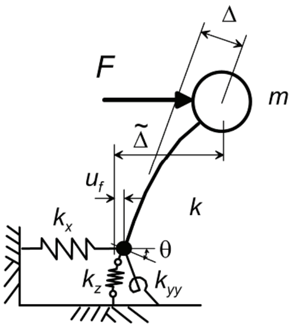

Fig. 1. Soil-Structure model

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Table 1. Soil properties

Layer	Depth (m)	Shear wave velocity (m/s)	Friction angle
1(Bottom)	10	375	37.5
2(Middle)	10	300	37.5
3(Top)	10	200	32.5

generalized to Multi-Degree-of-Freedom systems.

The lateral force and displacement values in this system are related by

$$\Delta = \frac{F}{k} + \frac{F}{k_x} + \left(\frac{F.h}{k_{yy}} \right) \tag{1}$$

where, h is the height of the lumped mass from the base; and k is the building stiffness in closed-end case

$$k = 4\pi^2 \left(\frac{W}{gT^2} \right) \tag{2}$$

where, g is the gravitational acceleration; $\widetilde{W}$ is the effective mass of the building. Thereby, the fundamental period of fixed-base building (T) is related to that of flexible-base building ($\widetilde{T}$) by

$$\frac{T}{T} = \sqrt{1 + \frac{k}{k_x} + \frac{k.h^2}{k_{yy}}} \tag{3}$$

3- Results and Discussion

The soil properties used for investigations are given in Table 1 adopted from [3].

Example 1: *4-story building*. This example is adapted from [5]. Figure 2 shows the model of the building and soil layers.

The DCR[1] values for columns of this building, in the optimal design, are shown in Figure 3. Results show that by considering SSI, the optimal design obtained for the fixed-base building, is no longer a feasible design.

Example 2: *12-story building*. This example is also adopted from [5]. Figure 4 shows the model of this building and the soil.

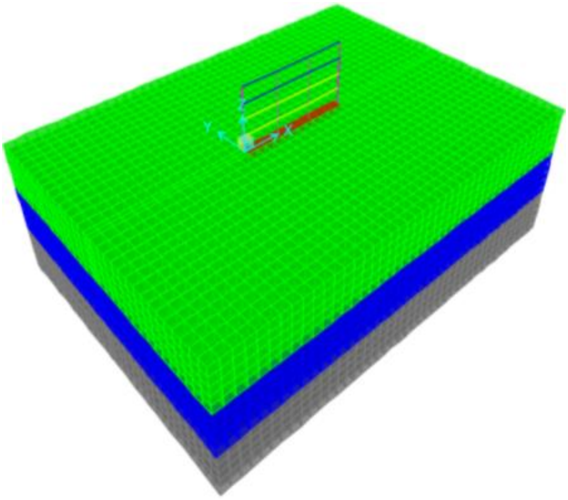

Fig. 2. story building

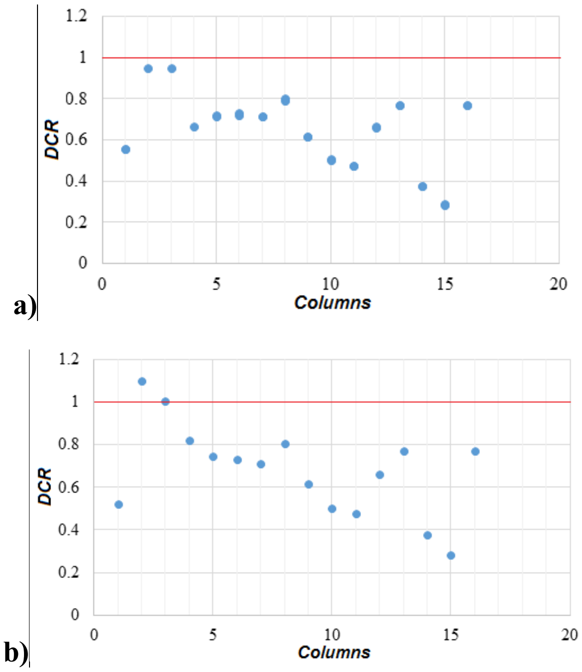

Fig. 3. DCR in columns of 4-story building; a) fixed-base, b) flexible-base

The DCR values for columns of this building, in the optimal design, are shown in Figure 5. Results show that by considering SSI, the optimal design obtained for the fixed-base building, exceeds the allowable DCR limit and is non-optimal and even infeasible.

Example 3: *24-story building*. The model of the building and the soil is shown in Figure 6.

The drift values of the stories of the optimally designed

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[1] Demand-to-Capacity Ratio

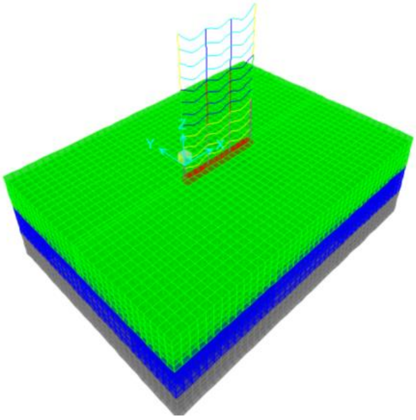

Fig. 4. 12-story building

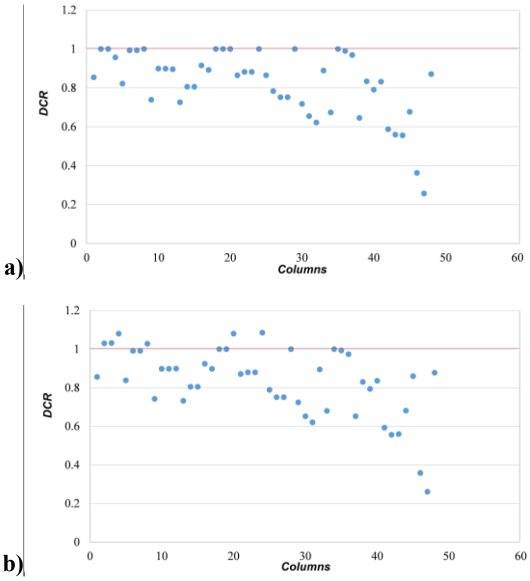

Fig. 5. DCR values for 12-story building; a) fixed-base, b) flexible-base

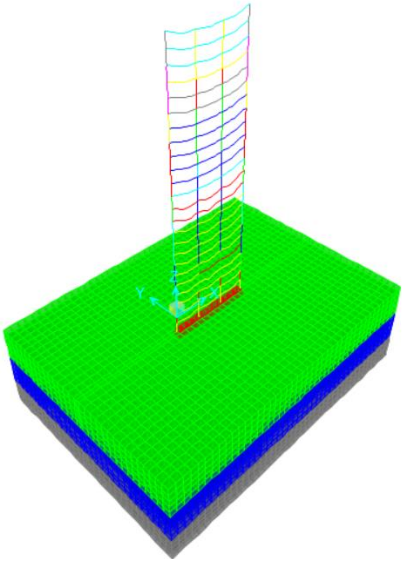

Fig. 6. 24-story building

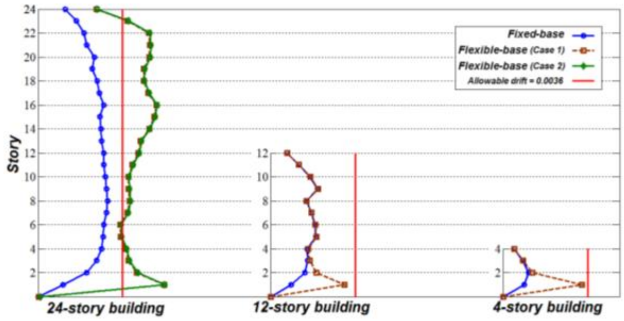

Fig. 7. Drift values in the investigated buildings

examples are compared with the allowable limit in Figure 7. The comparison shows that by considering SSI, the optimal design obtained for the fixed-base 24-story building, exceeds the allowable drift limit and is no longer a feasible design.

4- Conclusions

The conclusions of this study can be summarized as:

Generally, if the SSI effects are not accounted for in the design optimization of the building, then the obtained design may be not only non-optimal but also infeasible.

The results show that the SSI effect increases the stress in the columns for low- and mid-rise buildings. Also, it increases the story drifts for high-rise buildings.

According to the results, the SSI effect is more considerable in high-rise buildings compared to low- and mid-rise buildings.

The investigations on the high-rise 24-story building example show that the effect of the properties of a certain soil layer on the structural response is more important rather than the depth in which that layer exists. Hence, the characteristics of the different layers of the soil under the building should be studied to a sufficient depth.

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